LYMAN-ALPHA FOREST: 3D

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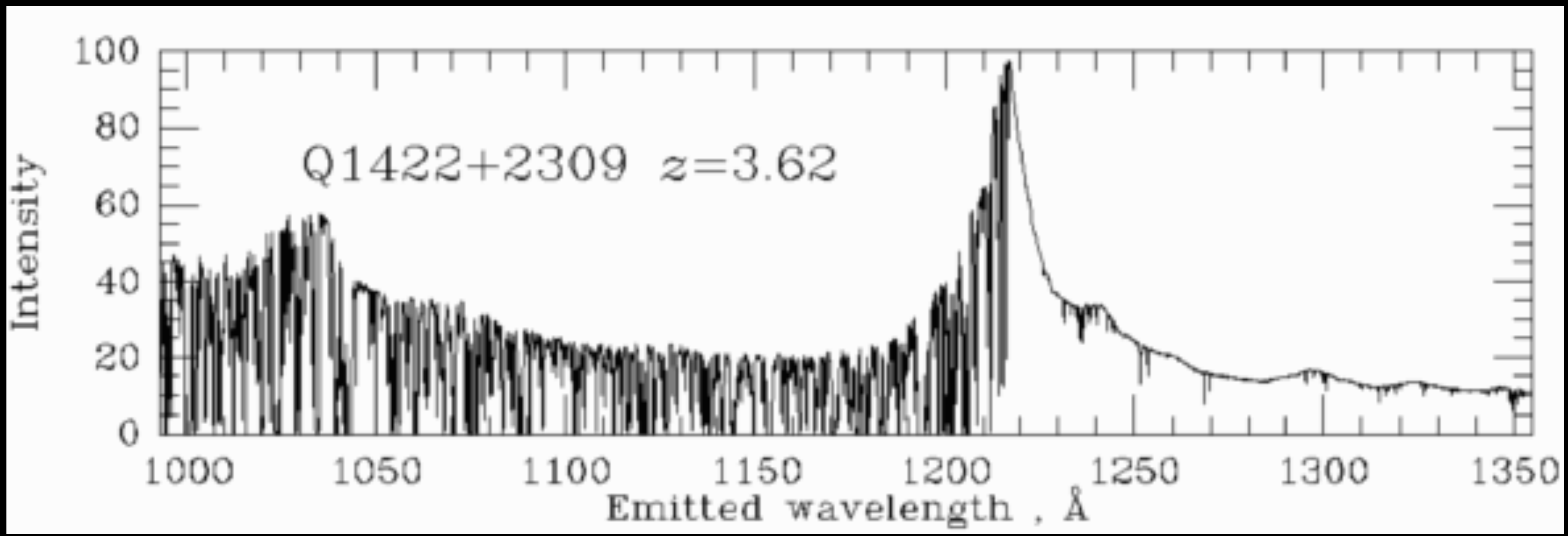
The Lyman-α Forest

1 Gpc

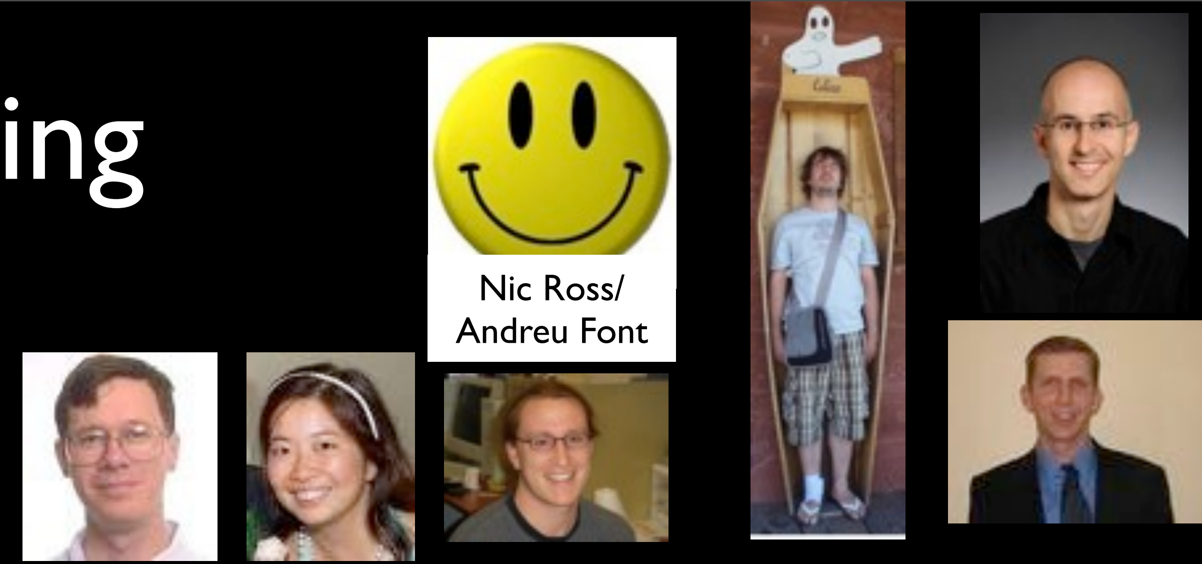


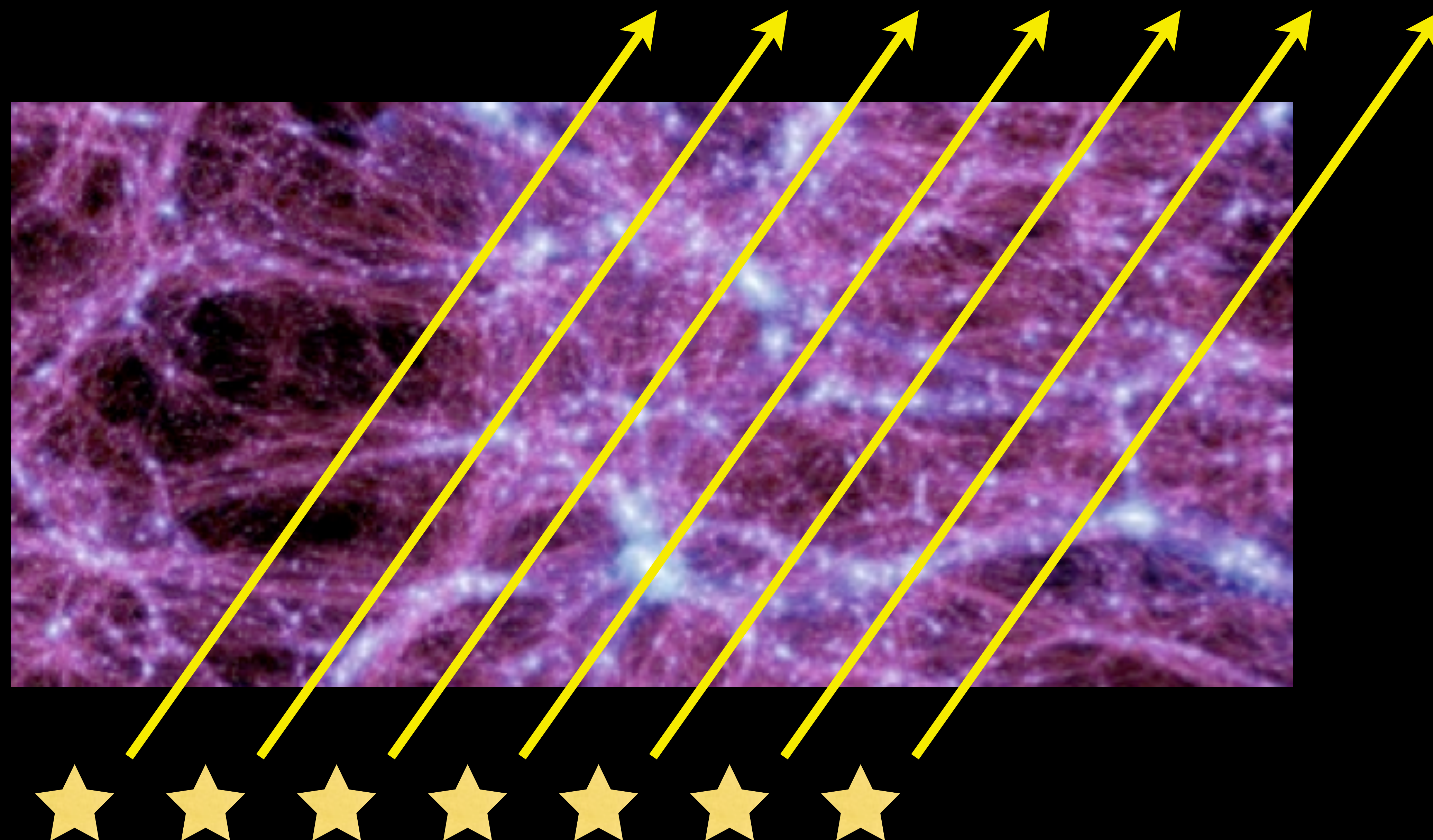
$$\tau_{\mathrm{Ly}\alpha} \approx 1.1\, \Delta_b^2\, T_4^{-0.7}\, \Gamma_{-12}^{-1} \left(\frac{1+z}{4}\right)^{9/2} \frac{H(z)/(1+z)}{dv/dx},$$

BOSS will take 160,000 of these!

(although, the above is R=70,000, S/N>100 whereas think R=2000, S/N>2)

3D Lyman-α Forest is being measured with BOSS





Previous theoretical work: McDonald 2003, White 2003, McDonald and Eisenstein 2007
Slosar et al (2010), White et al (2010)

Topics to tackle:

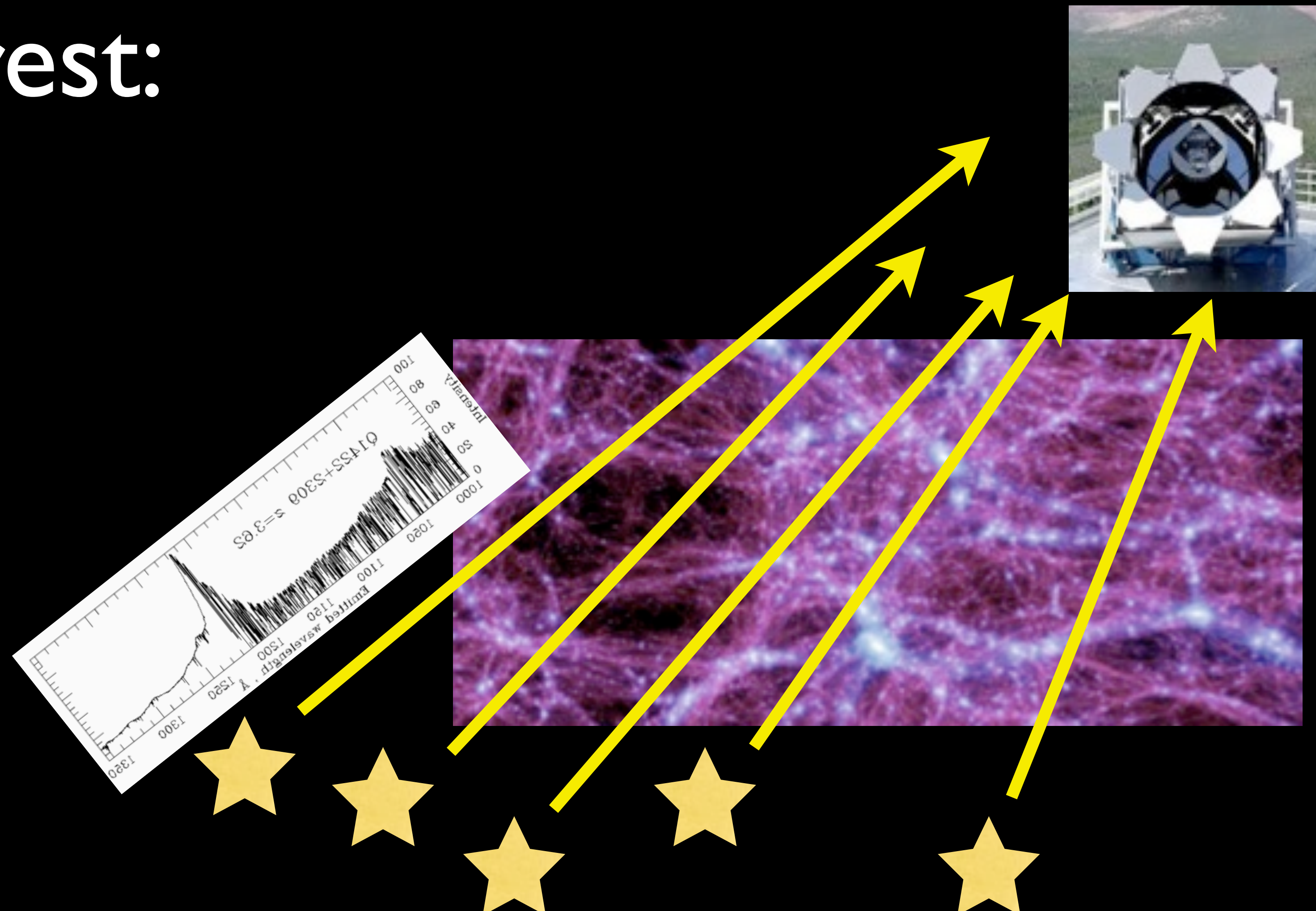
- What is sensitivity of a survey to 3D correlations in the flux? (a bit technical)

- What is the optimal design for a 3D Lyman-alpha survey?

- What are the interesting things to measure?

(talk will run on short side so please ask ?s)

How to best measure 2 pt correlations in the 3D Lyman-α Forest:



We want to estimate the power spectrum:

$$\widehat{P}_{\mathrm{F}}^{\mathrm{QE}} = \sum_{nm} Q_{nm}\, \tilde{\delta}_{\mathrm{F},n} \tilde{\delta}_{\mathrm{F},m} - \mathrm{tr}[Q\, C],$$

where

$$Q = \left(\mathrm{tr}\left[C^{-1} X\, C^{-1} X\right]\right)^{-1} C^{-1} X\, C^{-1}.$$

$$\begin{aligned} C_{nm} &= P(k_\parallel, r_{nm}) + P_{\mathrm{N},n}\, \delta_n^m, \\ X_{nm} &= \left(\frac{\Delta k_\perp}{2\pi}\right)^2 \exp[i k_\perp \cdot r_{nm}], \\ P(k_\parallel, r_{nm}) &\approx \int \frac{dk_\perp}{2\pi} k_\perp\, P_{\mathrm{F}}(k_\parallel, k_\perp)\, J_0(k_\perp\, r_{nm}) \end{aligned}$$

Goal: A nice expression for the S/N of estimator.

But quasar's transverse separation is large (>~10 Mpc) so C is diagonally dominated

$$\widehat{P}_{\rm F}^{\rm QE} = \sum_{nm} Q_{nm}\, \tilde{\delta}_{{\rm F},n} \tilde{\delta}_{{\rm F},m} - {\rm tr}[Q\, C],$$

(δ_F is the Fourier transform of the flux along sightline n)

where if we approximate off-diagonal in C as zero

$$Q_{nm}^{(0)} = A \left(\frac{2\pi}{\Delta k_\perp}\right)^2 \frac{\exp[i\, \boldsymbol{k}_\perp \cdot \boldsymbol{r}_{nm}]}{(P_{\rm los} + P_{{\rm N},n})\, (P_{\rm los} + P_{{\rm N},m})}$$

where A is just a normalization factor &

$$P_{\rm los}(k_\parallel) \equiv \int \frac{d^2 \boldsymbol{k}_\perp}{(2\pi)^2}\, P_{\rm F}(k_\parallel, \boldsymbol{k}_\perp),$$

is the line of sight power.

This diagonal approximation for the estimator is suboptimal at the percent-level for BOSS and 10% level for any conceivable quasar survey compared to the minimum variance estimator.

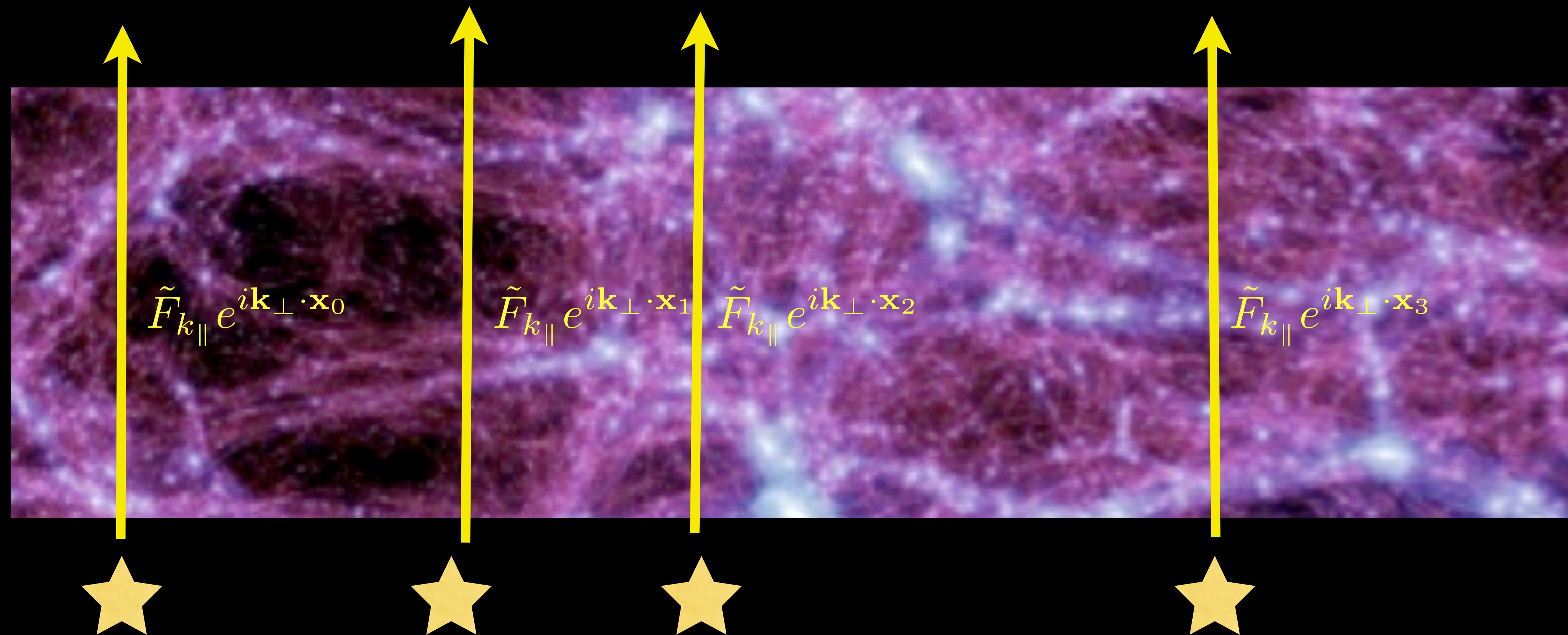
Minimum Variance Quadratic Estimator (cont)

-- Can write a matrix expansion (only involving matrix multiplications) that converges to minimum variance quadratic estimator.

--Next order term in the expansion suppresses the weight of spectra that have an overdensity of sources within $r_\perp \cdot k_\perp < 1$.

McQuinn & White (2010)

Alternatively, think Monte Carlo Integration



$$\text{3D Flux}(\mathbf{k}) = N^{-1} \sum_{\forall i} \tilde{F}_{k_\parallel, i} e^{i\mathbf{k}_\perp \cdot \mathbf{x}_i} \qquad \widehat{P}_{\mathrm{F}} = |\text{3D Flux}(\mathbf{k})|^{\mathbf{2}}$$

This is the traditional way of thinking about problem (McDonald and Eisenstein 2007, White et al 2010). It turns out to be identical to diagonal covariance approximation for quadratic estimator if you weight sight-lines by (total power)$^{-1}$.

Estimator also easily generalizable to correlation function: Equivalent to weighting each real space flux pixel by variance in flux over total variance (flux + noise), where variance is measured over a scale of > 10Mpc.

On a single mode, this estimator has variance:

$$\mathrm{var}[\widehat{P}_{\rm F}] = 2\,P_{\rm tot}^2$$

where

$$P_{\rm tot}(\boldsymbol{k}) = P_{\rm F}(\boldsymbol{k}) + \bar{n}_{\rm eff}^{-1}\,P_{\rm los}(k_\parallel)$$

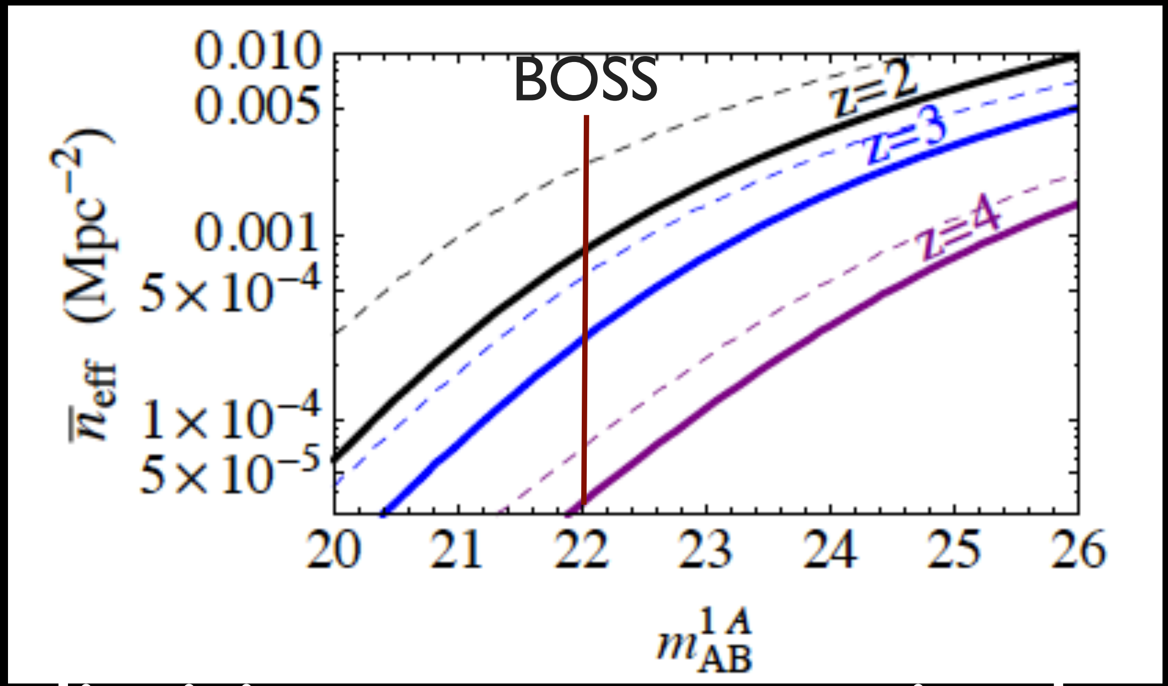
and

$$P_{\rm los}(k_\parallel) \equiv \int \frac{d^2\boldsymbol{k}_\perp}{(2\pi)^2}\,P_{\rm F}(k_\parallel, \boldsymbol{k}_\perp),$$

Sensitivity to P_F only depends on one #, n_{eff}!

where

$$\bar{n}_{\rm eff} \equiv \frac{1}{\mathcal{A}} \sum_{n=1}^{N} \nu_n, \quad \nu_n \equiv \frac{P_{\rm los}(k_\parallel)}{P_{\rm los}(k_\parallel) + P_{{\rm N},n}}$$



limiting quasar magnitude

n_{eff} depends extremely weakly on $k_{||}$ in practice over $k_{||}$ of most interest. One number determines the sensitivity of a survey!

It is simple to see how much weight is given each quasar.

$$\bar{n}_{\rm eff} \equiv \frac{1}{\mathcal{A}} \sum_{n=1}^{N} \nu_n, \quad \nu_n \equiv \frac{P_{\rm los}(k_\parallel)}{P_{\rm los}(k_\parallel) + P_{{\rm N},n}}$$

Table 3. Value of $\nu_n \equiv (1+P_{{\rm N},n}/P_{\rm los})^{-1}$ (c.f., eqn. 13) at several redshifts as a function of the S/N on the continuum in a 1 Å pixel.

$[S/N]_{1A}$	$z=2.2$	$z=2.6$	$z=3.0$	$z=3.6$	$z=4.0$
0.50	0.04	0.06	0.08	0.10	0.11
1.00	0.14	0.20	0.27	0.31	0.33
2.00	0.40	0.50	0.59	0.64	0.66
5.00	0.81	0.86	0.90	0.92	0.93
10.00	0.94	0.96	0.97	0.98	0.98

calculated at $k_{||} = 0.0014$ s km^{-1} but depends weakly on this

need S/N > 2 on continuum in 1A pixels for quasar to be useful

Effective Volume

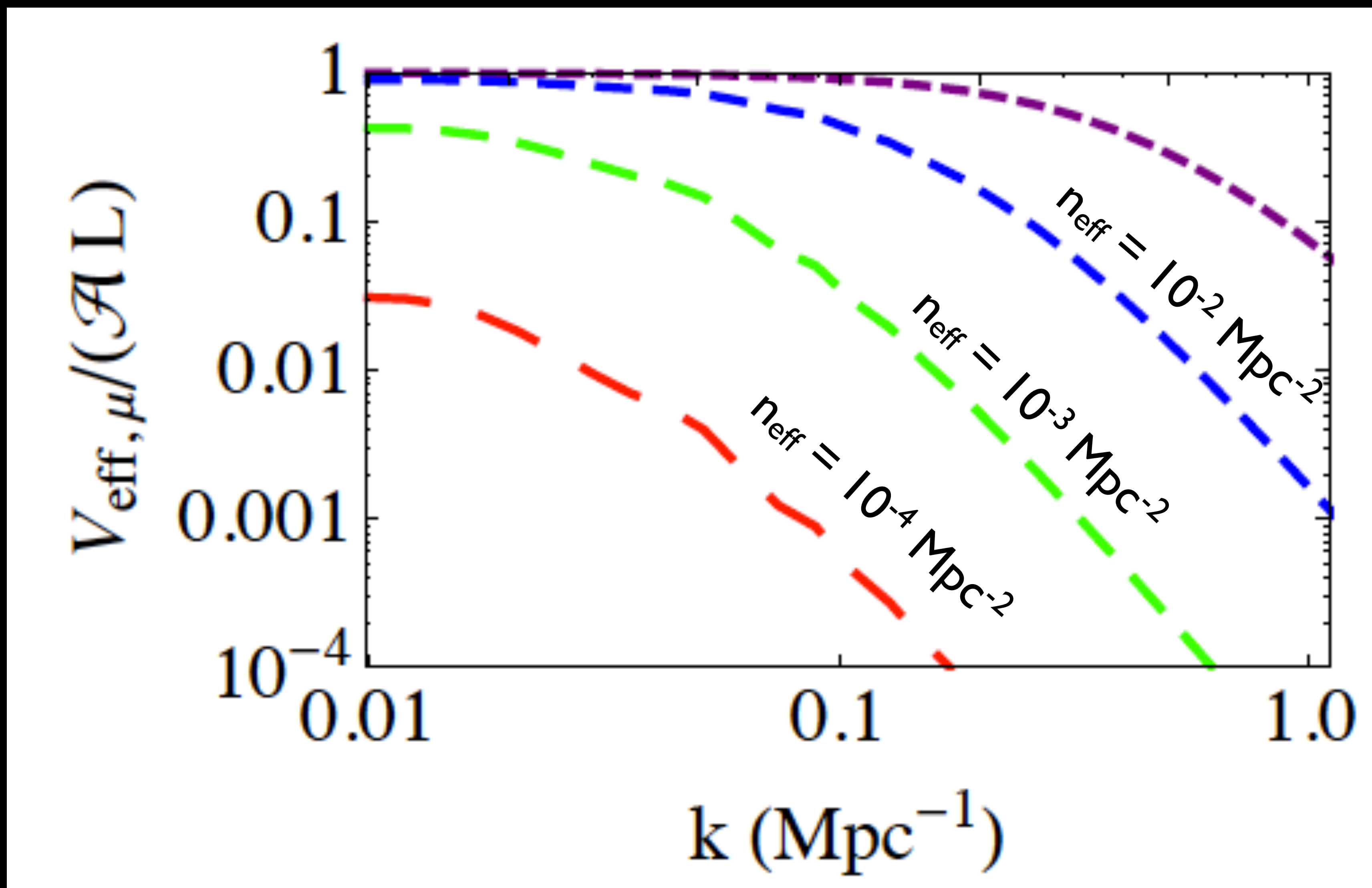
Galaxies:

$$V_{\mathrm{eff,g}}(k) \equiv V_{\mathrm{g}} \left(\frac{P_{\mathrm{g}}(k)}{P_{\mathrm{g}}(k) + \bar{n}_{\mathrm{g,3D}}^{-1}} \right)^2$$

Quasars:

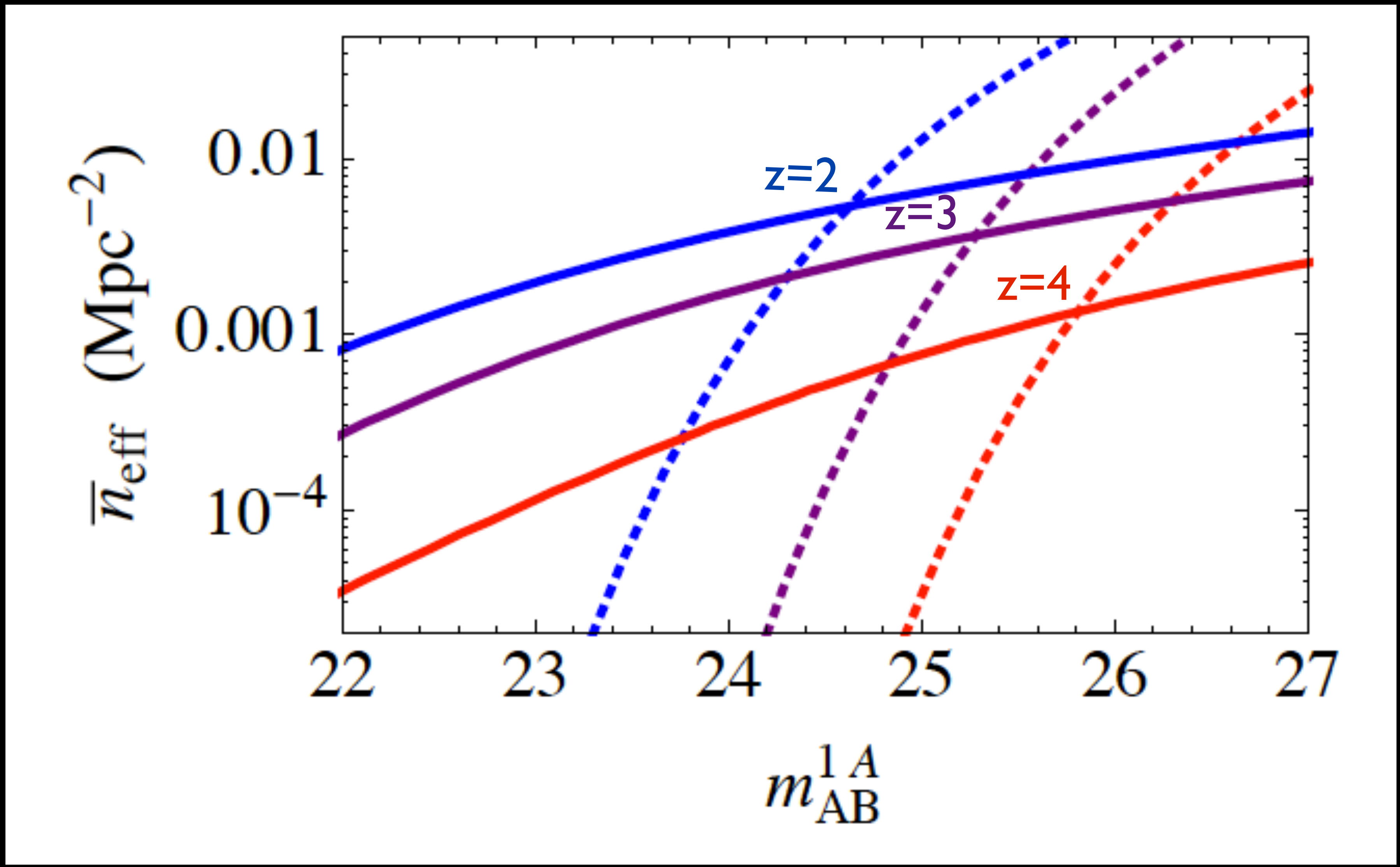
$$V_{\mathrm{eff}}(k) \equiv \mathcal{A} L \left(\frac{P_{\mathrm{F}}(k)}{P_{\mathrm{F}}(k) + \bar{n}_{\mathrm{eff}}^{-1} P_{\mathrm{los}}(k_{\parallel})} \right)^2$$

S/N on mode



BOSS can almost image large-scale modes at z~2!

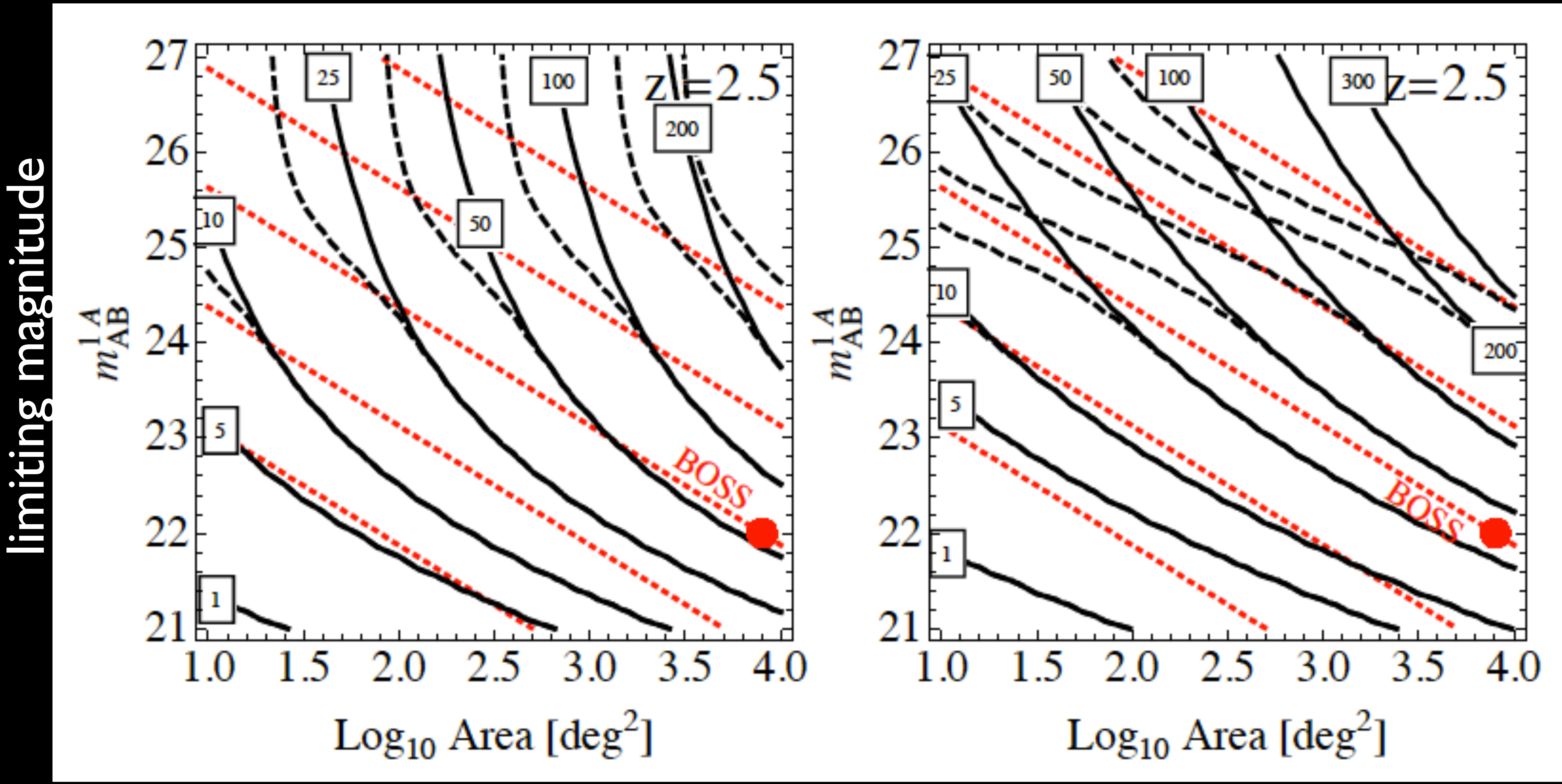
Using Forest from Galaxies



limiting quasar magnitude

Survey Design

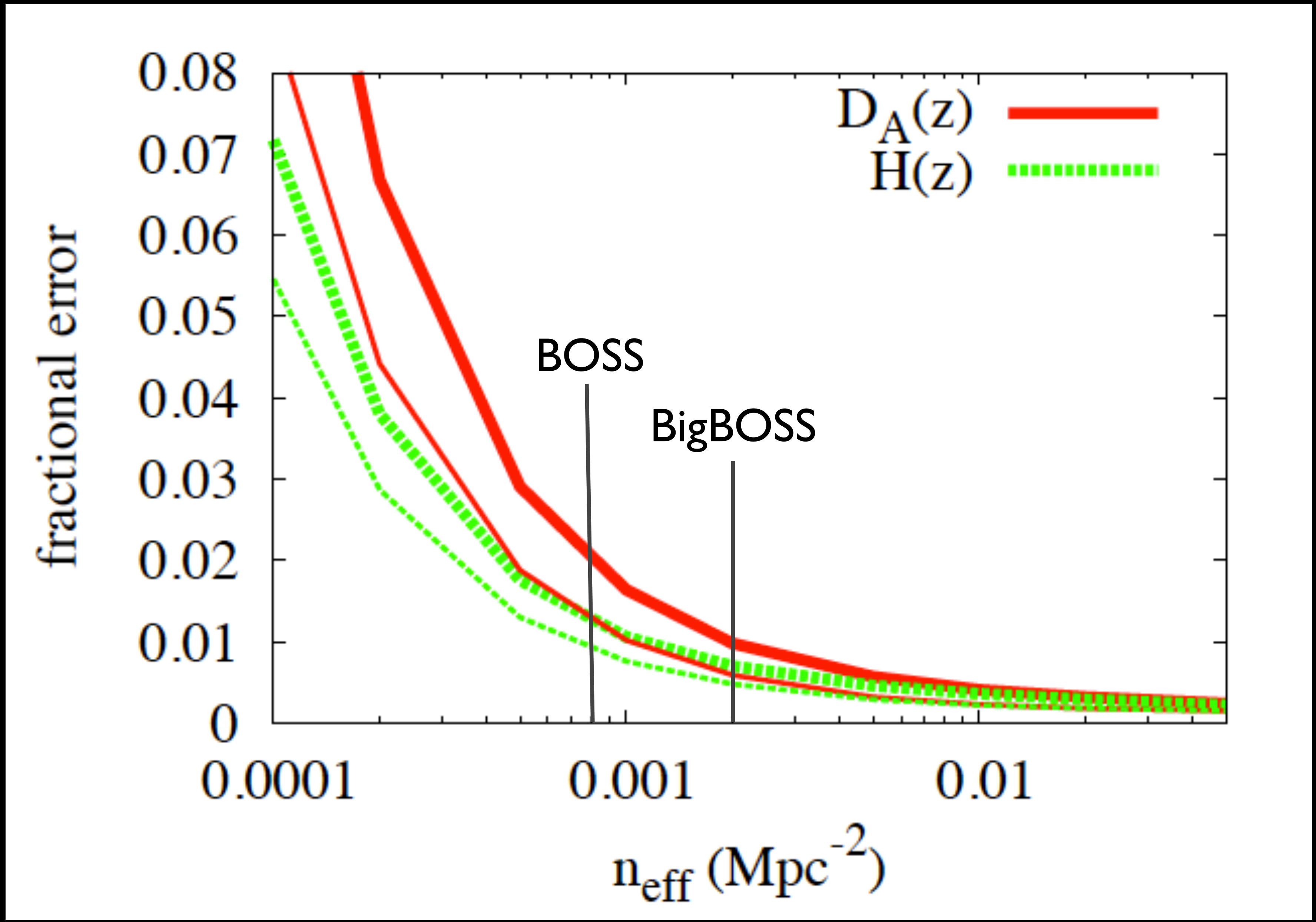
Red dashed: contours of constant (survey area)/(limiting flux)^2
solid black: contours of constant sensitivity (S/N on P in dk/k=0.2)



k = 0.1 Mpc^{-1} k = 0.5 Mpc^{-1}

Cosmological Constraints from BAO

Assumes area $A=10^4$ deg^2 and depth L=1 Gpc, but scales as [AL]^{-1/2}



$$\delta\Omega_k \approx 0.26\,\delta D_A/D_A$$

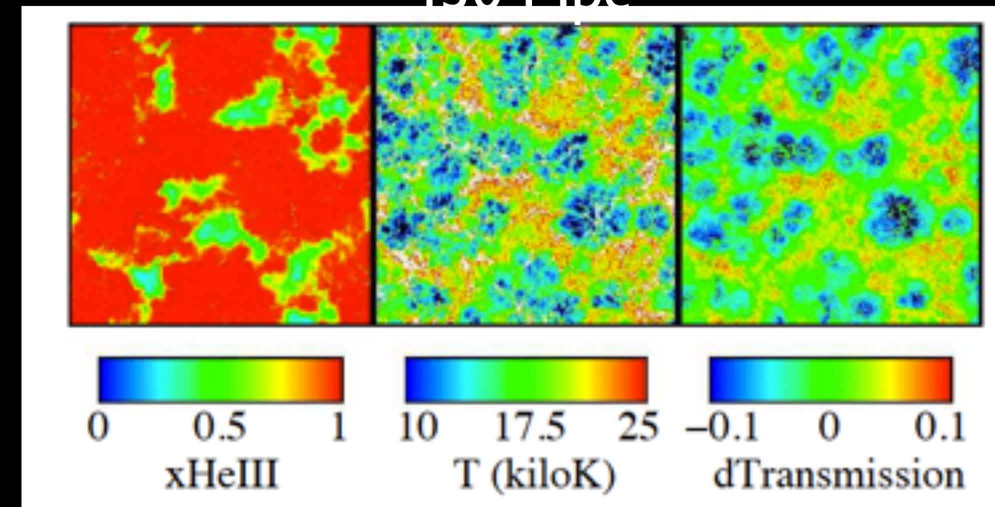
Now that I’ve got you trapped.....some

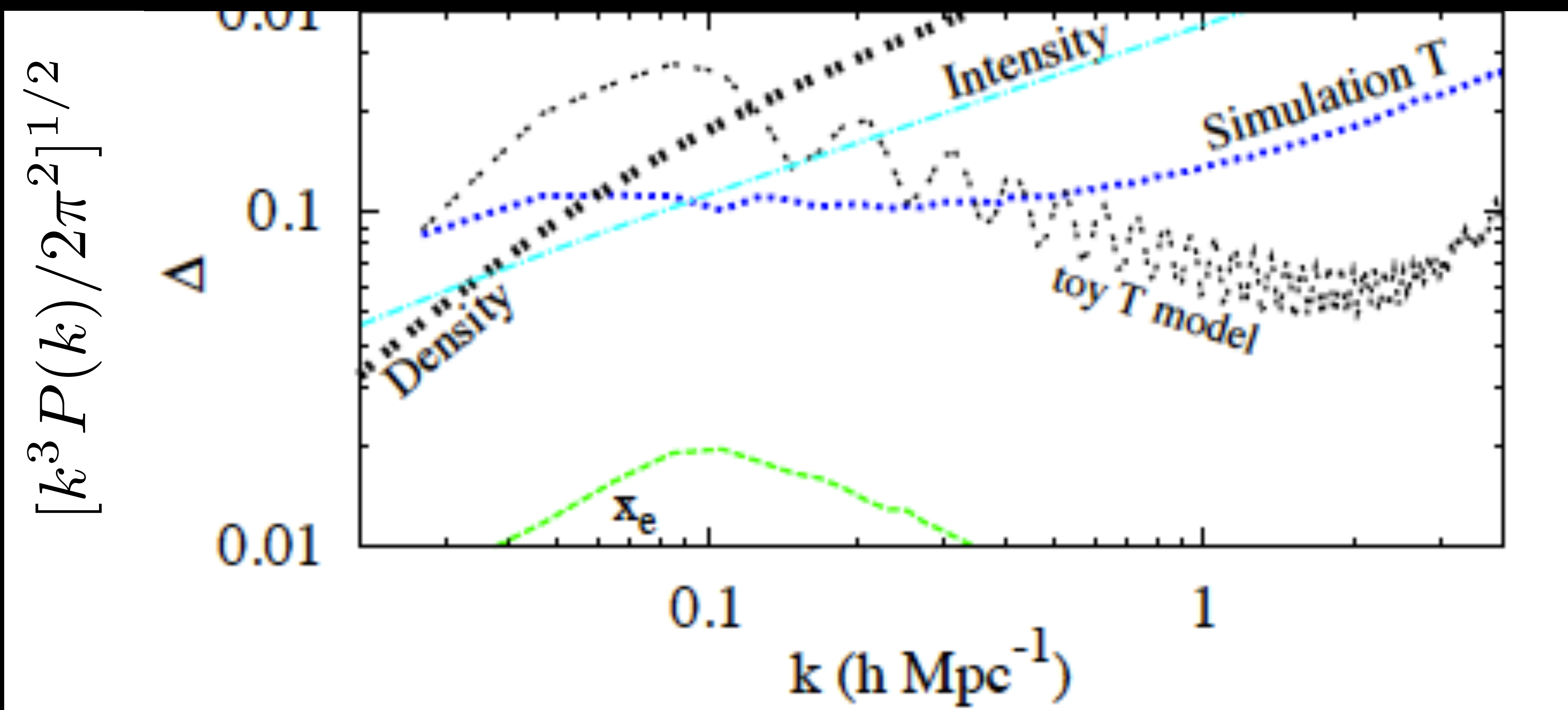
Astrophysics

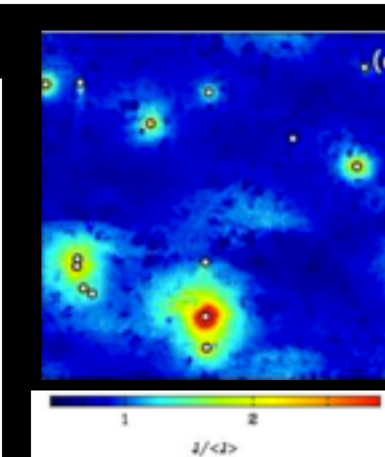
Contributions to Lyα forest Fluctuations

$$\tau_{\mathrm{Ly}\alpha} \approx 1.1\,\Delta_b^2\,T_4^{-0.7}\,\Gamma_{-12}^{-1}\left(\frac{1+z}{4}\right)^{9/2}\frac{H(z)/(1+z)}{dv/dx},$$

430 Mpc

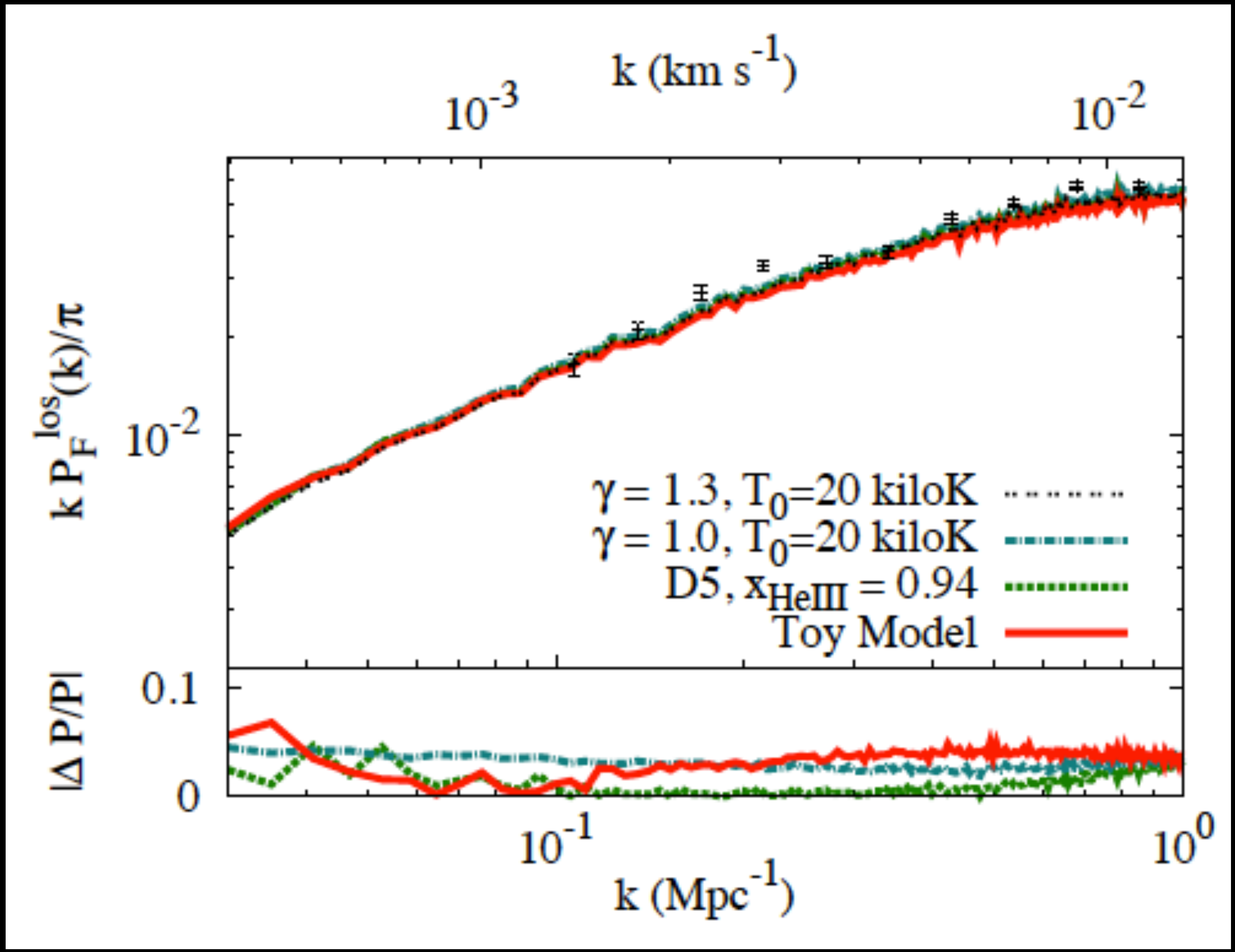






Intensity fluctuations in Croft '03

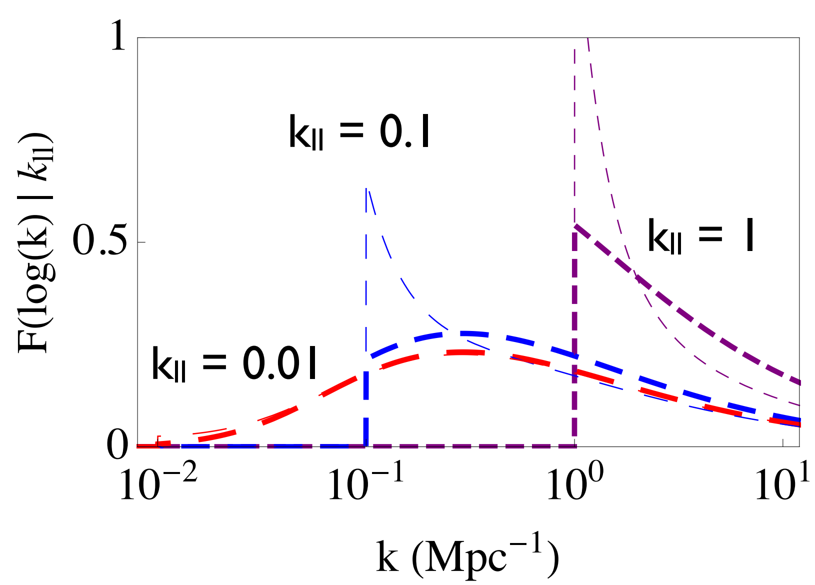
Effect of temperature fluctuations on line-of-sight power spectrum is small (also see Lai et al (2005)



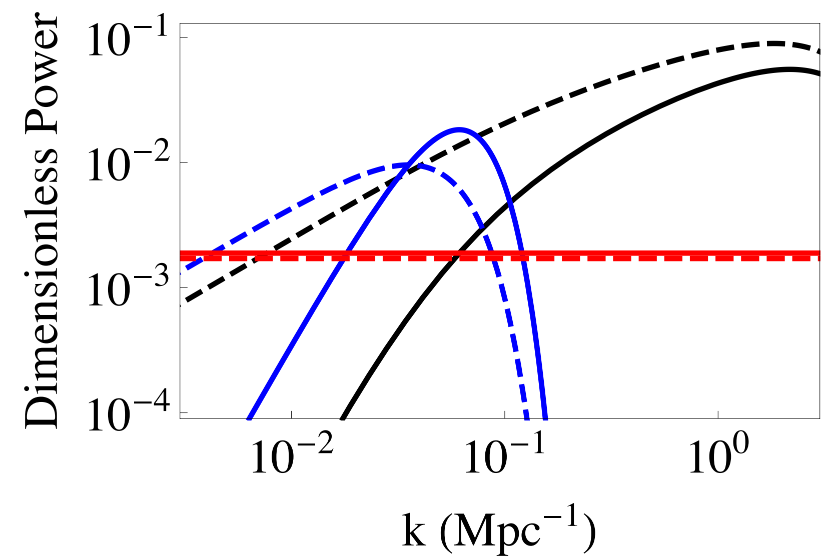
Similar conclusions hold for intensity (Croft '03, McDonald et al 05)

Have very small effect in 1D

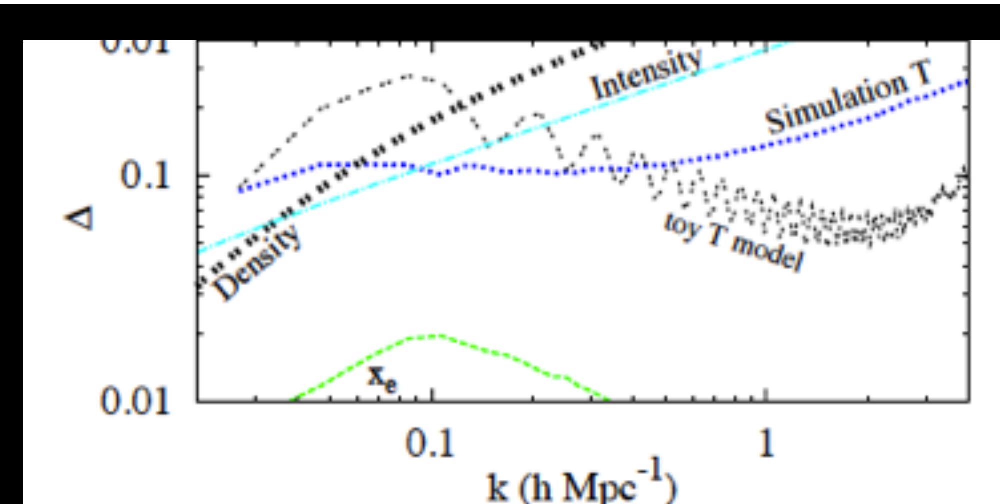
The contribution of different 3D modes to line-of-sight mode



3D and 1D power spectra for same input spectrum



$$P_F^{\rm los}(k_\|) = \int_{k_\|}^{\infty} \frac{dk}{2\pi} k\, P_F(k, k_\|/k)$$

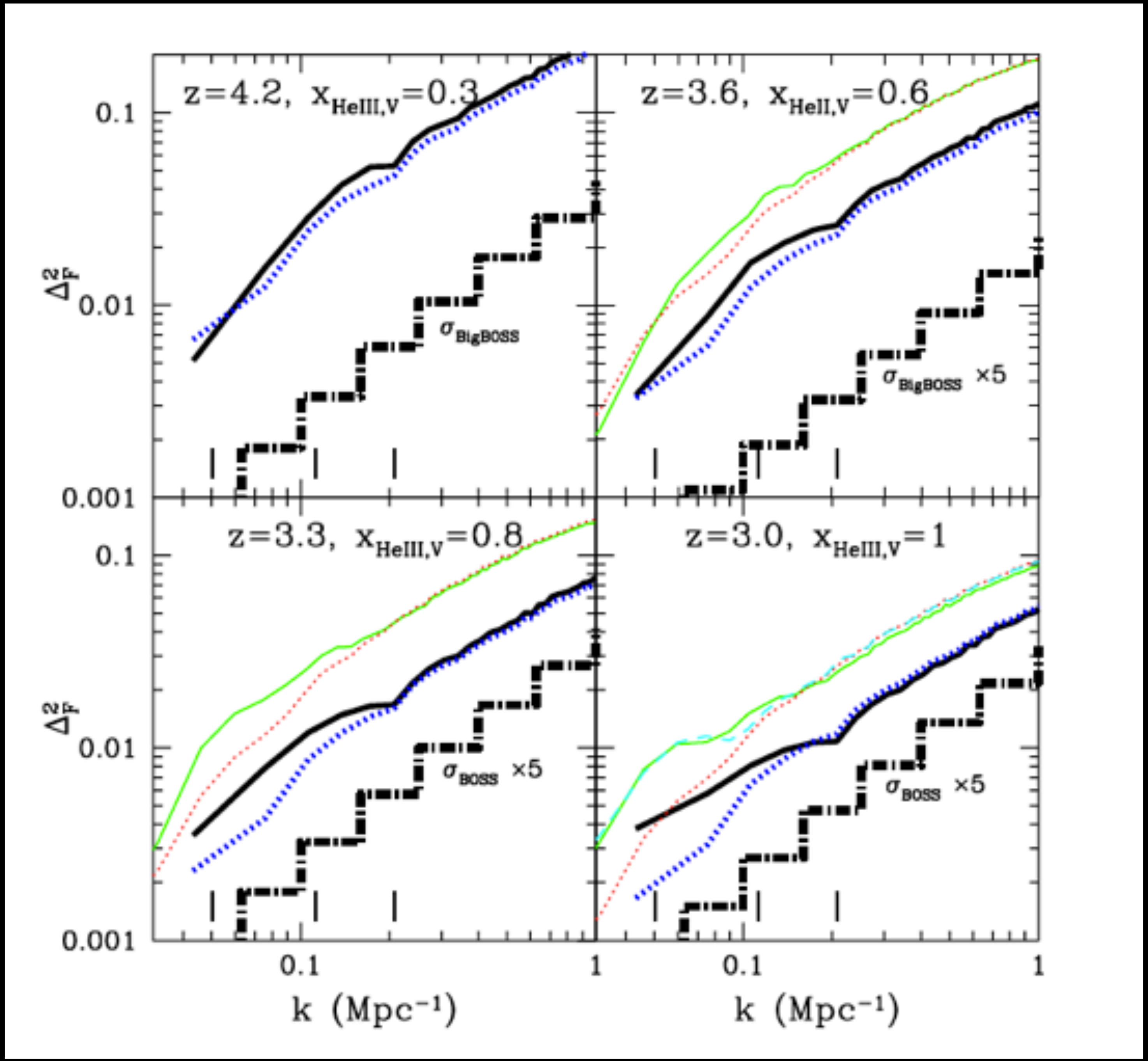


Effect of Temperature Fluctuations using temperature fluctuations in simulation of HeII reionization

$$P_F(k) \approx b^2\Big(G^2 P_\Delta(k) + 2G\epsilon^{-1}\left[P_{\Delta\,Tp7}(k) - P_{\Delta\,J}(k)\right] + \epsilon^{-2}\left[P_{Tp7}(k) + P_J(k)\right]\Big)$$

$\epsilon \approx 2 - 0.7\,(\gamma - 1)$. The $G \equiv (1 + g\mu^2)$

Here, "BOSS" is a survey with limiting magnitude of 22 in 8000 deg^2 and BigBOSS is a magnitude fainter



We have nice formula for relative impact of T fluctuations; McQuinn et al (2011)

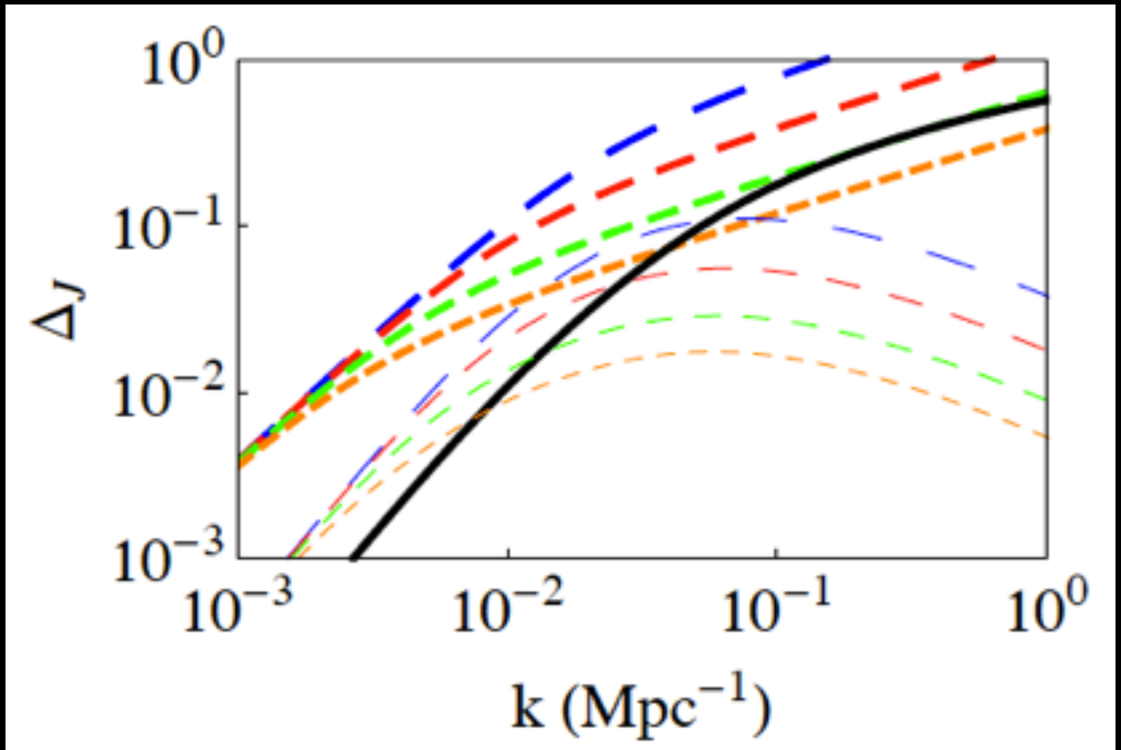
Intensity Fluctuations

$$P_F(k) \approx \tilde{P}_F(k) + b^2\left[\epsilon^{-2} P_J(k) - 2\,\epsilon^{-1}(1+g\mu^2)\,P_{\Delta J}(k)\right]$$

For infinite quasar lifetimes and fixed attenuation length:

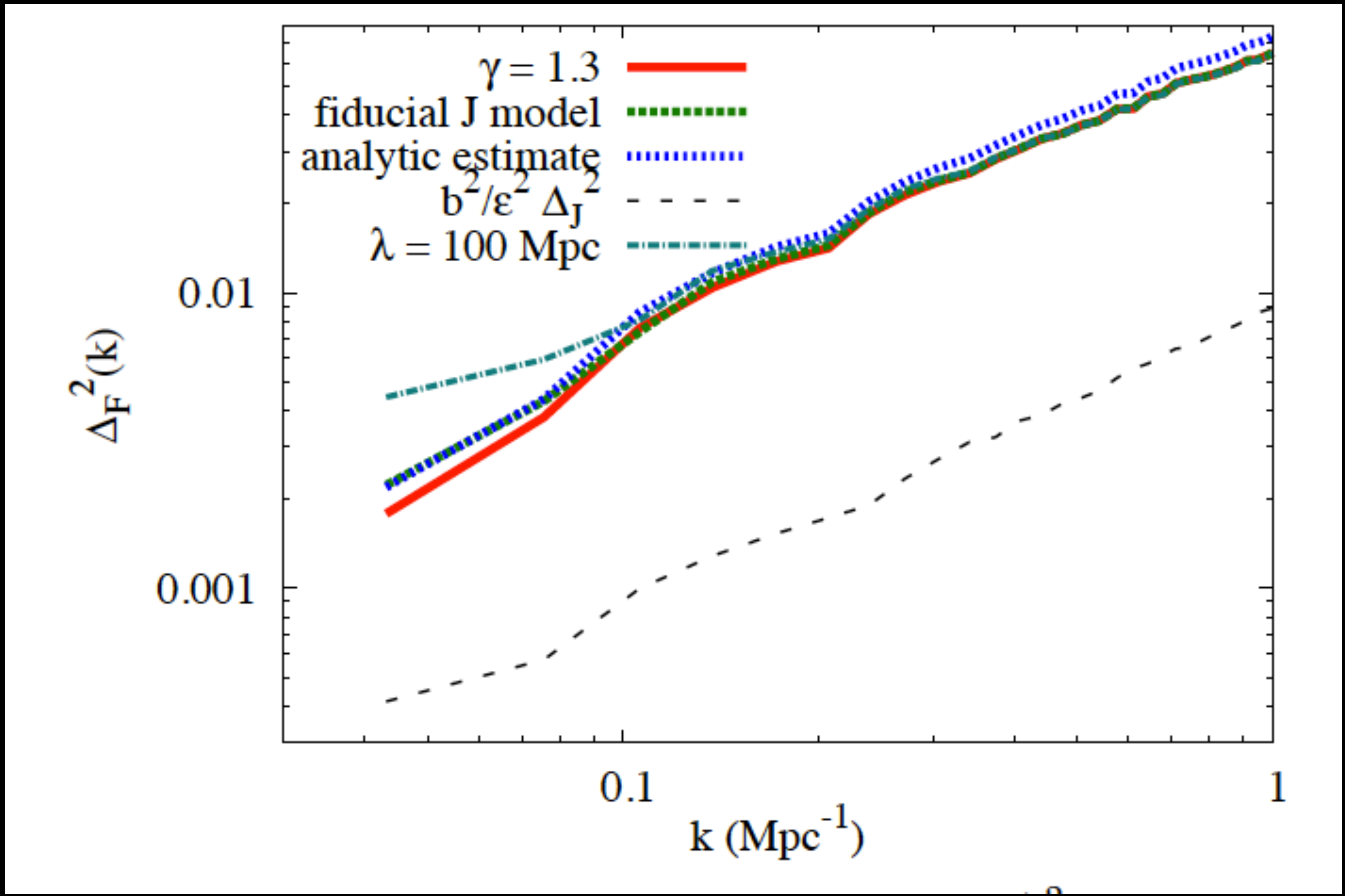
$$P_J = \left(\frac{\arctan(\lambda k)}{\lambda k}\right)^2 \left(\frac{\langle L^2\rangle}{\bar{n}\,\langle L\rangle^2} + b_q^2\,P_\Delta(k)\right)$$

<L^2>/<L>2 very sensitive to bright end of quasar LF



curves assume $\lambda = 500, 300, 150,$ and 70 Mpc

Effect of Intensity Fluctuations

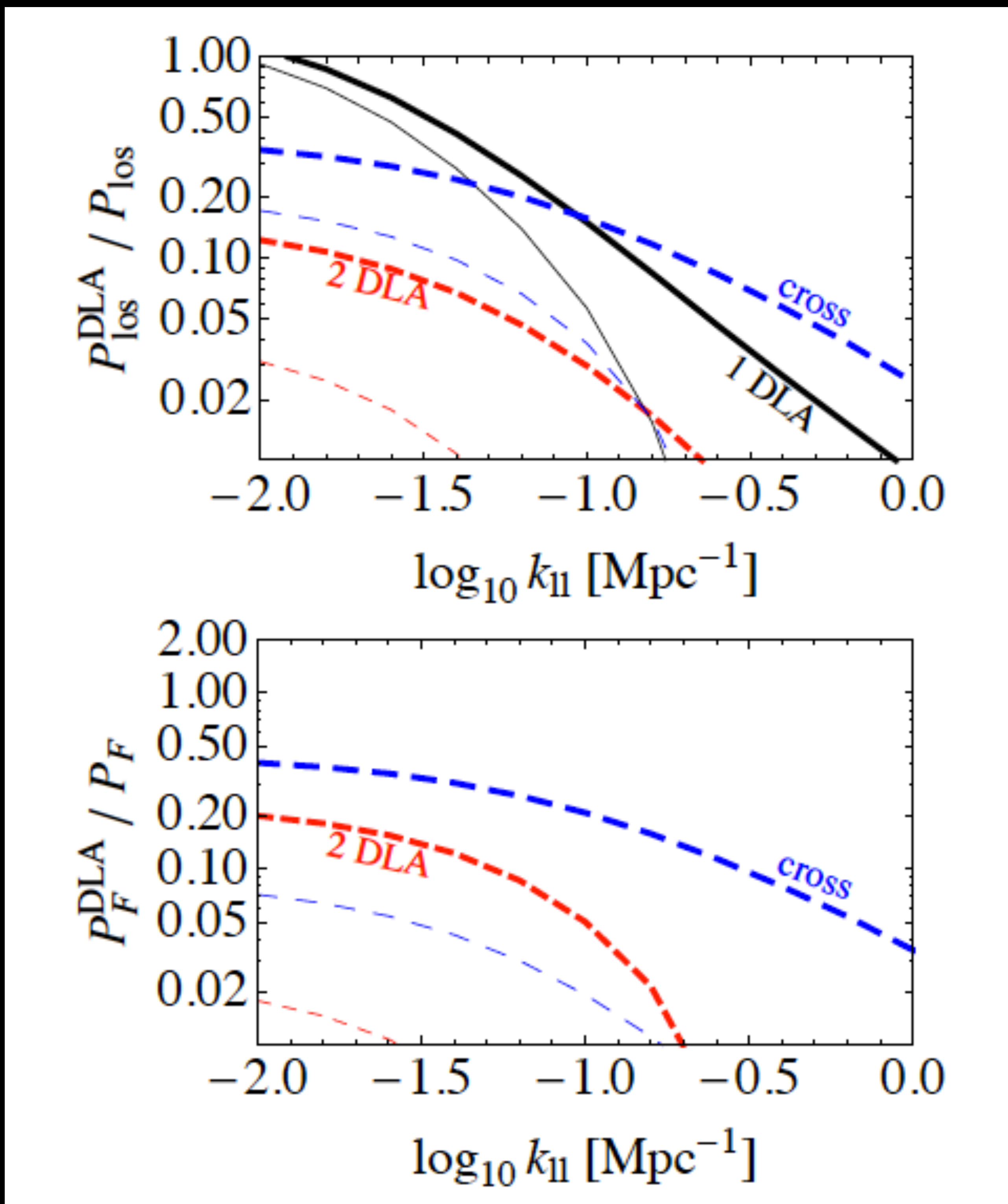


Also see Slosar, Ho, White & Louis '10

Conclusions

- If you want to estimate the sensitivity of any 3D Lyα survey, only need one number, n_{eff}, and you can easily calculate it's sensitivity
- In general, want equivalent of S/N> 2 in 1A pixels for a quasar to carry much weight.
- The rule of thumb is to go deep enough to capture all quasars with $L > L_*$
- May be able to measure H(z), D_A, temperature power, intensity power, quasar bias, DLA bias etc
- 3D Lyα surveys are awesome!

DLAs



$$P_{\rm F}^{\rm DLA} = \widetilde{W}_2(k_\parallel)^2 \, (b_{\rm DLA} + \mu^2)^2 \, P_\delta^{\rm lin}(k), \tag{B1}$$

$$P_{\rm los}^{\rm DLA} = \widetilde{W}_1(k_\parallel) + \widetilde{W}_2(k_\parallel)^2 \int \frac{dk_\perp}{2\pi} k_\perp (b_{\rm DLA} + \mu^2)^2 \, P_\delta^{\rm lin}(k),$$

where we have neglected the shot noise component in $P_{\rm F}^{\rm DLA}$ because it is small on relevant scales and

$$\widetilde{W}_1(k_\parallel) = \int dN_{\rm HI} \, \frac{\partial^2 \mathcal{N}}{\partial\chi \partial N_{\rm HI}} \tilde{d}(k_\parallel)^2, \tag{B2}$$

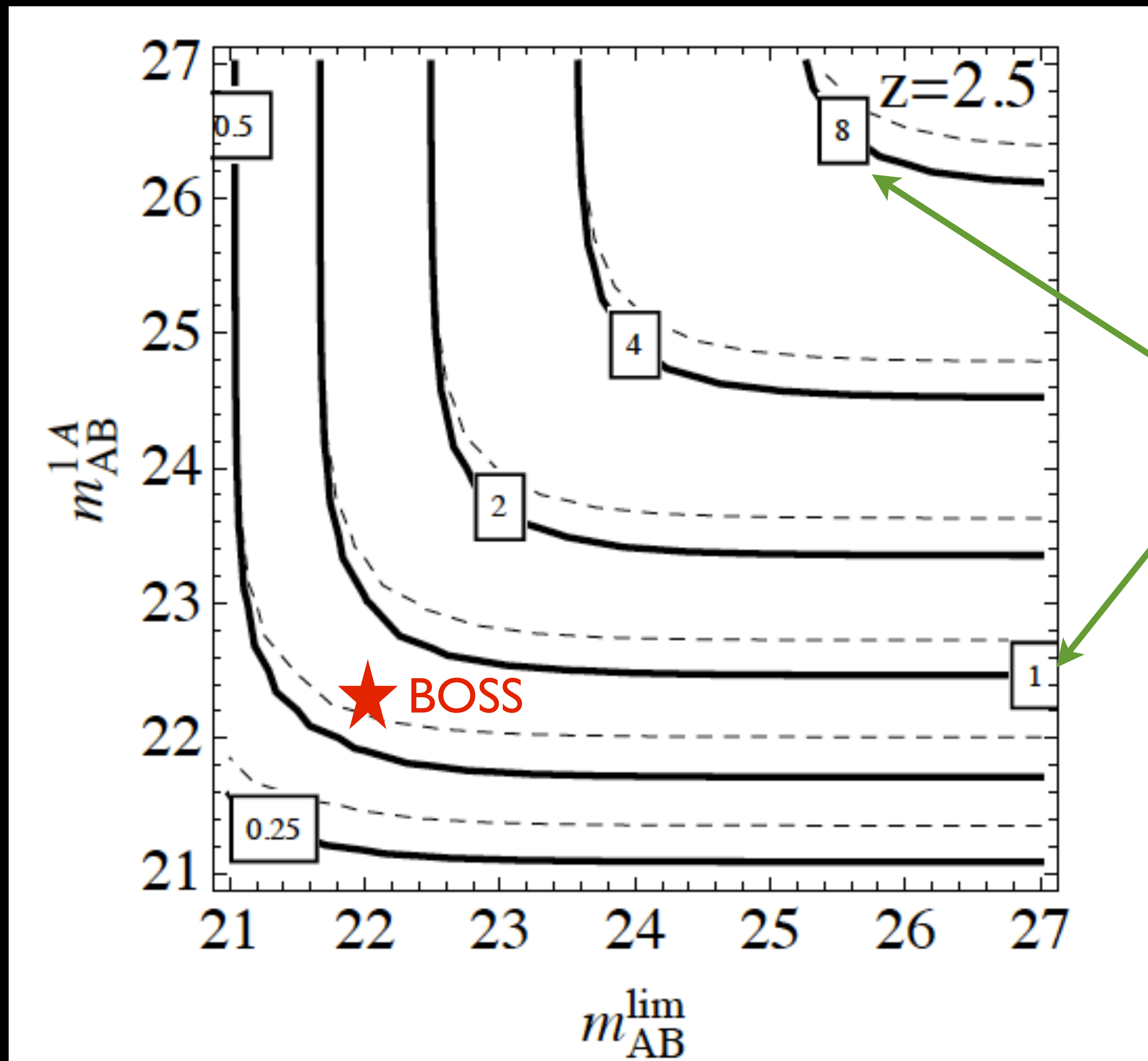
$$\widetilde{W}_2(k_\parallel) = \int dN_{\rm HI} \, \frac{\partial^2 \mathcal{N}}{\partial\chi \partial N_{\rm HI}} \, \tilde{d}(k_\parallel), \tag{B3}$$

contours of constant $n_{\rm eff}$

$\mathrm{var}[P_\mathrm{F}] = 2\,P_\mathrm{tot}^2$

$P_\mathrm{tot}(\boldsymbol{k}) = P_\mathrm{F}(\boldsymbol{k}) + \bar{n}_\mathrm{eff}^{-1}\,P_\mathrm{los}(k_\parallel)$

quasar magnitude at which spectra have S/N=1 in 1A pixels



$n_{\rm eff}$ in units of 10^{-3} Mpc^{-2}

limiting quasar magnitude